

Impact of micro-combined heat-and-power systems on energy flows in the UK electricity supply industry

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Abstract

The effects of applying micro-CHP systems to a single dwelling, and to various dwellings within a group, are investigated by using gas and electricity consumption data recorded on a 1-min time base across a full year. Micro-CHP systems based on Stirling engines and fuel cells are predicted to supply 25–46% of the single dwelling's annual electricity demand. For all days of the year, the daily load factor of the resultant load placed on the electricity network is reduced, suggesting that the overall effect of micro-CHP systems will be to provide highly dispersed base-load generation. Consideration of various penetration levels of a 1 kW Stirling engine micro-CHP system of 15% electrical efficiency indicates that the maximum reduction in the aggregate peak load for a single distribution transformer will be about 44% on a winter's day, but only 3% on a summer's day. An alternative implementation of 3 kW fuel cell systems of 50% electrical efficiency would yield significant reductions (both in the peak load and the daily requirement for network electricity) at low penetration levels, with significant reverse flows occurring at the distribution transformer once the penetration level exceeds approximately 15% on a winter's day.

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1. Introduction

The need to reduce CO₂ emissions per unit of delivered energy is central to the development of future power systems. The integration of micro-combined-heat-and-power (μ CHP) systems, which supply electricity and heat to individual dwellings, is now being facilitated by the development and demonstration of reliable prime movers of micro-scale. These are generally envisaged as mass-market products for reducing household energy-costs and carbon emissions, with potentially several million individual implementations in the UK domestic sector. When compared with the planning constraints associated with the long-term expansion of onshore wind generation or other intermittent renewable energy (RE) technologies (and the concomitant transmission reinforcement and storage issues), the introduction of μ CHP generation within the capacity of the existing low

Abbreviations: ADMD, After diversity maximum demand; FC, Fuel cell; LV, Low voltage; MV, Medium voltage; RE, Renewable energy; SE, Stirling engine; μ CHP, Micro-combined-heat-and-power

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Nomenclature

E_{gen}	Electrical power generated by stated μ CHP system that is used by the dwelling, kW
E_{exp}	Electrical power exported to the network by a dwelling or group of dwellings employing the stated μ CHP system, kW
E_{imp}	Electrical power imported from the network by a dwelling or group of dwellings employing the stated μ CHP system, kW
e	Electrical energy requirement of the stated dwelling or groups of dwellings, kWh
e_{gen}	Electrical energy generated by the stated μ CHP system that is used by the dwelling, kWh
e_{imp}	Electrical energy imported from the network by a dwelling or group of dwellings employing the stated μ CHP system, kWh
e_{exp}	Electrical energy exported to the network by a dwelling or group of dwellings employing the stated μ CHP system, kWh
LF	Daily load factor, the ratio of the average electrical demand to peak demand across a period of one day, %
n	Proportion of homes with a μ CHP system, %
P_e	Electrical demand of the stated dwelling or group of dwellings, kW
P_q	Heat demand of the stated dwelling or group of dwellings, kW
P_{oe}	Electrical power output of the μ CHP prime mover, kW
P_{ot}	Recovered thermal power rating of the μ CHP prime mover, kW
Q	Heat requirement of the stated dwelling or group of dwellings, kWh
Q_{imp}	Heat import from the auxiliary boiler by a dwelling with the stated μ CHP system, kW
Q_s	Heat output generated by the stated μ CHP system that is deemed surplus to the dwelling's requirements, kW
Q_{used}	Heat output generated by the stated μ CHP system that is usefully employed by the dwelling, kW
Q_{st-in}	Heat output generated by the stated μ CHP system that is directed to the thermal store, kW
Q_{st-out}	Heat import from the thermal store by a dwelling with the stated μ CHP system, kW
q_{imp}	Heat requirement from the auxiliary boiler by a dwelling with the stated μ CHP system, kWh
q_s	Heat generated by the stated μ CHP system that is deemed surplus to the dwelling's requirements, kWh
q_{used}	Heat generated by the stated μ CHP system that is usefully employed by the dwelling, kWh
T_{max}	Maximum temperature setting of thermal store, °C
T_{min}	Minimum temperature setting of thermal store, °C
T_{store}	Temperature of thermal store, °C
ζ_b	Efficiency of the central heating boiler (i.e. thermal output divided by fuel input), %
ζ_e	Electrical efficiency the μ CHP prime mover (i.e. useful electrical output divided by fuel input), %
ζ_{hr}	μ CHP heat recovery efficiency (i.e. the proportion of the otherwise wasted heat that is usefully recovered), %

voltage (LV) network appears relatively straightforward. However, this type of embedded generation is likely to remain within the control of individual consumers and cause intermittent bi-directional flows of electricity at the lowest level of the power system. Consequently, it is an entirely distinct form of embedded generation, which requires careful research attention. The intention of this paper is to provide a detailed assessment of the electrical supply/demand matching impacts of generic μ CHP systems upon (i) a single dwelling and (ii) a distribution transformer serving a group of dwellings, by using heat and power demand profiles recorded for individual dwellings on a time base of 1 min across a period of 1 year.

The deployment of μ CHP systems may become a key plank of the UK government's efforts to decarbonise the electricity supply because of the improved overall efficiency of CHP when compared with conventional practice and the potentially large reductions in utility bills for consumers [1]. It is these two levers that may

encourage the adoption of μ CHP systems in the domestic space heating market place. These aspects have been addressed in two recent publications by the authors using similar technology and control assumptions to those considered here [2,3]. However, there is also a third, often neglected, factor that may effect the deployment of these systems: μ CHP has the potential to alter the load profile for network electricity met by central generation. This is a significant factor, because the domestic sector is the main contributor to the evening peak and the substantial gradients that occur on the national daily load profile. The effect of implementing μ CHP systems may therefore be to assist or exacerbate the load profiles met by primary electricity generation and hence their operating schedules and specific carbon emissions [4].

In the UK, μ CHP systems are defined as generating units rated at up to 16 A per phase, likely to be single phase and connected within a domestic or light commercial property [5]. Prime mover capacities of up to about 3.7 kW are therefore of interest. Four distinct prime mover technologies are under development for application as μ CHP systems—solid oxide fuel cells [6], proton exchange membrane fuel cells [7], internal combustion engines [8] and Stirling engines [9,10]. Of these, systems based on Stirling engines (SE) are graduating beyond the demonstration phase and now being marketed as replacements for conventional domestic central-heating boilers (without requiring modification of the building's existing space-heating and hot-water infrastructure). Their operation will be intrinsically linked to the thermal demand of an individual dwelling, which is a complex function of the weather, building design, occupancy and behavioural factors.

The future penetration level of μ CHP systems in the LV network is difficult to predict, but an ultimate deployment equivalent to the entire gas-fired boiler market would represent about 18 million implementations or approximately 75% of the UK domestic building stock. An estimate of the UK market potential for SE systems of 13.5 million units has been made [11], and assuming a nominal unit size of 1 kW, this represents 13.5 GW of installed capacity (i.e. approximately equivalent to 22% of the UK 2002 peak winter demand [12]). However, the application of different types and sizes of micro-generator, plus implementations that are independent of the gas network may ultimately result in an even greater installed capacity within the electricity network, and/or locally high penetration levels. For example, in Germany it has been estimated that 25% of the residential power demand could be provided by fuel cell μ CHP [13], while a carbon reduction approach has recently been identified for the UK where up to 50 GW of highly dispersed μ CHP and RE generation is deployed within the LV network by 2050 [14].

Two recent studies [15,16] have investigated the effect upon the LV network of a mass deployment of μ CHP systems with prime movers of 1.1 kW. The impact of deploying μ CHP systems at a penetration level (n) of 100% was to substantially reduce the load placed on the LV network. During periods of minimum load (0.16 kW per dwelling) an export flow that constituted approximately 580% of the original load was generated at $n = 100\%$ with an unacceptable voltage rise being forecasted when n reached 40–50% [15]. However, penetration levels of up to 100% appear feasible in urban locations, providing certain steps are taken to reconfigure the LV network so that voltages always remain below the statutory limit. The economic cost of accepting more than 17 GW of micro-generation within the British networks was reported to be substantially less than the wider benefits attributable to this level of deployment [16]. Clearly, changes in energy flows of this magnitude would have significant impacts upon network utilisation and the operating schedules of primary thermal power plant. The nature of such changes however will be a function not only of the penetration level, the prime mover size and the control strategy employed to operate the μ CHP systems, but also of the diversity of load occurring within LV networks containing the micro-generators.

Previous predictions of energy savings arising from the deployment of μ CHP systems have largely been based on the annual or daily delivery of heat and power to a dwelling relative to a non-CHP reference case [11], or by citing the results of commercial trials without indicating the underlying performance information [18]. Independent field trials have recently been initiated in the UK to evaluate the performance of commercially available μ CHP systems [19]. Modelling the performance of μ CHP systems is highly dependent on the temporal precision with which both the thermal and electrical demand is considered. For instance, the environmental outcomes of μ CHP deployment have been reported to vary by up to 40% depending on the temporal resolution of the analysis undertaken [17]. Transient variation in thermal and electrical demand is clearly a major variable that will determine the applicability and performance of μ CHP for a specific dwelling.

2. Micro-CHP system simulation

2.1. Energy demands and system definition

A previously recorded database of energy demand data [4] was employed to provide demand information for simulating the performance of a μ CHP system in a single dwelling. This consists of electricity and gas consumption data, which were recorded for 30 detached dwellings in central England, with 13 dwellings being monitored concurrently for a minimum period of one calendar year. In each of the 13 dwellings, space heating was provided solely by gas-fired central heating boilers and the recorded gas consumption data applies only to these boilers. As such, it is indicative of the aggregate space heating and hot water demands. The exact periods of heat demand per day were assumed to correspond to the gas utilisation profile, which was a function of the thermal load, the on/off time settings of the boiler and any override decisions made by the user. Computation of the time-varying boiler efficiency was not feasible, because boiler supply and return temperatures were not monitored. Thus, for the purposes of this investigation, it was simply assumed that the heat requirement was equivalent to the recorded gas consumption. The dwelling had respective annual heat and electricity consumptions of 17.5 and 5.8 MWh, and an annual heat-to-power ratio of 3.0. This compares to 2001 averages for UK domestic dwellings of 19.0 and 3.4 MWh for heat and electricity consumption, respectively [20]. The annual heat and electricity consumptions of the remaining 12 dwellings were within the ranges $13.7 < q < 42.0$ and $3.4 < e < 7.1$ MWh, respectively. In general, annual heat and electricity demands vary across wider ranges than those applying to the available dataset, for instance annual heat-to-power ratios range from about 2 for a flat, to 8 for an old large detached dwelling. It should be noted that the following analyses of the single dwelling and of the group of dwellings are not necessarily representative of a UK average scenario.

The heat-and-power demands of single dwellings show considerable minute-by-minute fluctuations owing to a large number of factors. To illustrate this, three days were selected from the single dwelling dataset for detailed investigation. These were (i) the day of maximum heat demand, (ii) a day in mid-season, and (iii) a summer day. The winter day, January 25th, had a daily heat-to-power ratio of 8.5 (Table 1), the heat demand occurred from morning until night and coincided with 87% of the electrical demand. The spring day, April 29th, had an intermediate heat requirement with a daily heat-to-power ratio of 3.7 and the heat demand occurred in distinct periods; 79% of the electrical demand occurred coincidentally. The summer day, August 21st, had a low heat demand and the daily heat-to-power ratio was only 0.6. The demand coincidence was much lower than on the other days, with only 32% of the electrical demand taking place during the periods of heat demand.

μ CHP systems are characterised principally by prime mover size (P_{oe}), electrical efficiency (ζ_e) and heat-recovery efficiency (ζ_{hr}) [2,3]. Two prime mover technologies were considered to address the influence of electrical efficiency: SEs and fuel cells. These represent one market ready and one potential future scenario for μ CHP deployment. In practice, their supply/demand matching performance will be influenced by the transient characteristics of the prime mover (e.g. stop-start and load-following capability) but, in the absence of more detailed information, the prime movers considered here were assumed to operate at rated power only and to have a perfect start-up characteristic. Similarly, a heat-recovery efficiency of 90% was assumed throughout, although this will clearly be a function of the prime mover heat-rejection temperature and the time-varying return temperature of the central-heating system. On this basis three synthetic generic μ CHP systems were defined for modelling purposes (Table 2).

Table 1
Heat-and-power demands of the single dwelling on January 25th, April 29th and August 21st

Parameter	January 25th	April 29th	August 21st
q (kWh)	151.1	82.6	10.0
e (kWh)	17.8	23.5	17.9
Heat: power ratio	8.5	3.7	0.6
Concurrence of heat demand with power demand (%)	87	79	32

Table 2
Operating parameters of μ CHP systems modelled

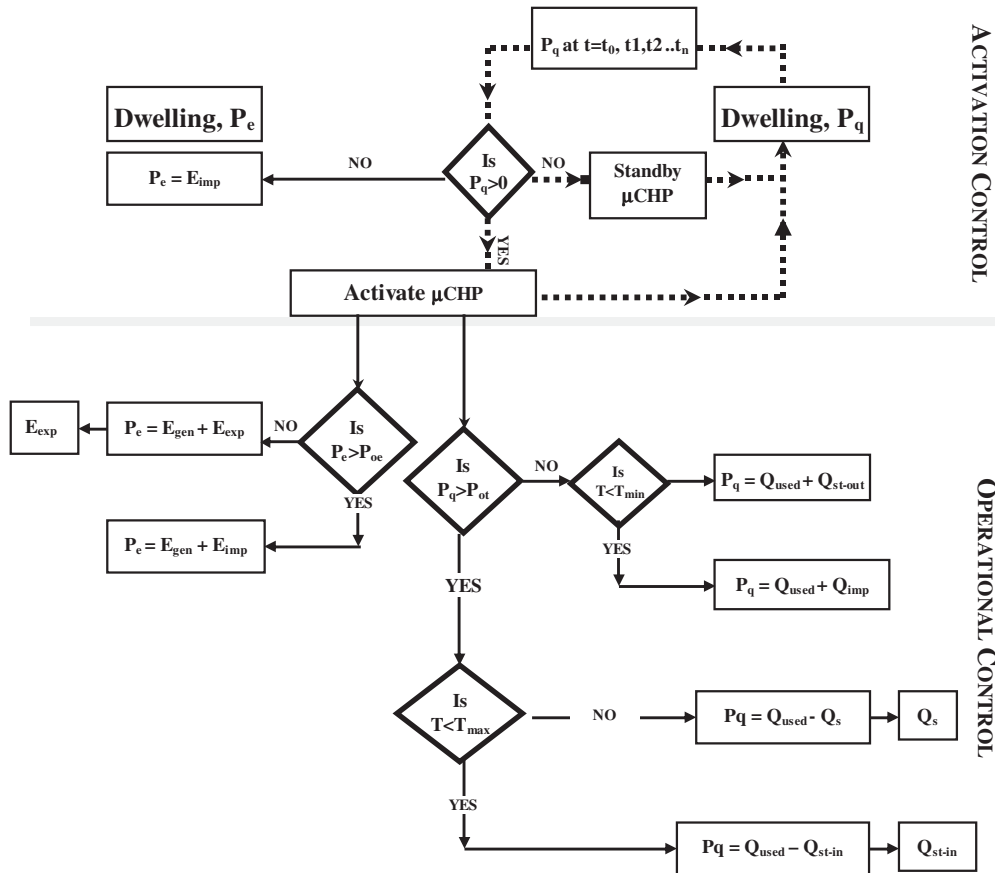
Prime mover technology	P_{oe} (kW)	ζ_e (%)	ζ_{hr} (%)	P_{ot} (kW _{th})
Stirling engine	1	15	90	5.1
Fuel cell	1	50	90	0.9
Fuel cell	3	50	90	2.7

Besides a prime mover and heat exchanger, a μ CHP system may include a thermal store, an auxiliary boiler, and even electrical storage/reconversion equipment. System operation may be regulated by a control logic based on the home's transient requirements for heat and power, perhaps in combination with external factors such as the import and export price for μ CHP generation. However, from the aforementioned demand characteristics of an individual dwelling, it is evident that a single co-generation unit will not be able to satisfy all of the household's heat-and-power demands, without recourse to supplementary sources of heat and power. The system design investigated here therefore comprised a μ CHP unit, an auxiliary gas-fired condensing boiler (where $\zeta_b = 90\%$), a thermal store and a network connection (for importing and exporting electricity as necessary).

2.2. Control logic

The μ CHP control logic defines the basis on which the prime mover is activated, deactivated or turned down. The “heat-led” control logic adopted here is shown in Fig. 1. When the power generated by the μ CHP system, P_{oe} , is less than that required (i.e. $P_e > P_{oe}$) the difference, E_{imp} , is imported from the electricity network. Conversely when $P_e < P_{oe}$, it is assumed that the difference, E_{exp} , is exported to the network. It is further assumed that E_{exp} incurs negligible losses before it reaches a point of use. The heat that is recovered by the μ CHP system from the prime mover, P_{ot} , is directed to meeting the space-heating demand, hot-water demand, or to the thermal store for later use. If $P_q < P_{ot}$, it is assumed that the difference ($P_{ot} - P_q$) is directed to a domestic hot-water tank of 150 l nominal capacity. This thermal store was assumed to operate between set point temperatures of 55 and 70 °C and to incur standing losses commensurate with that of a factory-insulated hot-water tank housed in a cold attic space. If the temperature of the store is at or above the maximum set point, it cannot receive energy and so a surplus of heat is produced if μ CHP operation is permitted to continue. If $P_q > P_{ot}$, the thermal store is employed to meet the remaining heat demand except when it is below its minimum set-point temperature whereupon the required shortfall, Q_{imp} , is produced by the auxiliary boiler. The boiler is assumed to be of sufficient capacity to provide the required Q_{imp} and to operate at a conversion efficiency equivalent to the heat-recovery efficiency of the μ CHP system (regardless of the heat load). This conforms to proposed μ CHP system designs, which comprise of a μ CHP systems and an auxiliary boiler within one integrated appliance, (i.e. strictly a cogeneration-and/or-heating system rather than a combined heat-and-power system).

Previous investigations have considered simple control approaches for a winter day and a summer day (such as continuous operation, idealised electrical load-following operation and time-controlled operation) [3,21]. An identified design problem was that of maximising daily savings on the summer day, due to the μ CHP system having to be shut down once the heat demand had been met. Any μ CHP heat generation in excess of this ‘heat limit’ is surplus to requirements. A subsequent study [2] showed that if μ CHP systems were operated without controlling this thermal surplus, the attributable CO₂ savings would be substantially reduced or even negated when compared to the non-CHP option (i.e. the use of a condensing boiler and the use of network electricity). Although avoiding any thermal surplus is desirable, the control logic also needs to ensure the number of switching events for the prime mover is limited, because the lifetimes of both engine and FC technologies are predicated by operating duty. One associated control method has been reported for the Whispergen Model PPS24-ACLG, a SE μ CHP prime mover [9]. Once the heat demand of the dwelling has been met this unit continues to operate at low power for 30 min in anticipation of a further heat requirement; if no further heat demand occurs during this period then it is deactivated.

Fig. 1. μ CHP system design and control.

Consequently, the control logic adopted here was a simple heat-led option where the μ CHP system is activated by a heat demand in the dwelling, but only if $P_q > P_{ot}$ or if $P_q < P_{ot}$ and $T_{store} < T_{max}$. After initiation, a “minimum run time” of 30 min at rated power was imposed as a base case. This control restriction was applied throughout unless otherwise stated. The effect of this minimum run time criterion was to increase the operational run time of the μ CHP systems. For instance the total operational time of the SE system increased by 2%, 4% and 5% on January 25th, April 29th and August 21st, respectively with commensurate impacts on electricity generation.

3. Results

3.1. Supply/demand matching—single dwelling

The greatest daily thermal demand of the dwelling occurred on January 25th and, with the aforementioned control logic, this resulted in the longest μ CHP system run time. On this day the run time was not restricted by the thermal output of the μ CHP system—for each of the simulated systems (Table 2) operation spanned the full period of thermal demand (i.e. 988 min). As a result, the amount of μ CHP electricity generation, e_{gen} , was a function only of the electrical output of the prime mover (with the operating performance of the 1 kW SE and 1 kW FC prime movers being identical).

Fig. 2 shows the impact of deploying μ CHP prime movers on the electrical demand of the dwelling on January 25th. The 1 kW μ CHP systems had a substantial impact on e_{imp} causing it to fall from 17.8 to 7.6 kWh (Fig. 2a, Table 3). The peak load was reduced from 6.1 to 5.1 kW, while the average load fell from 0.74 to

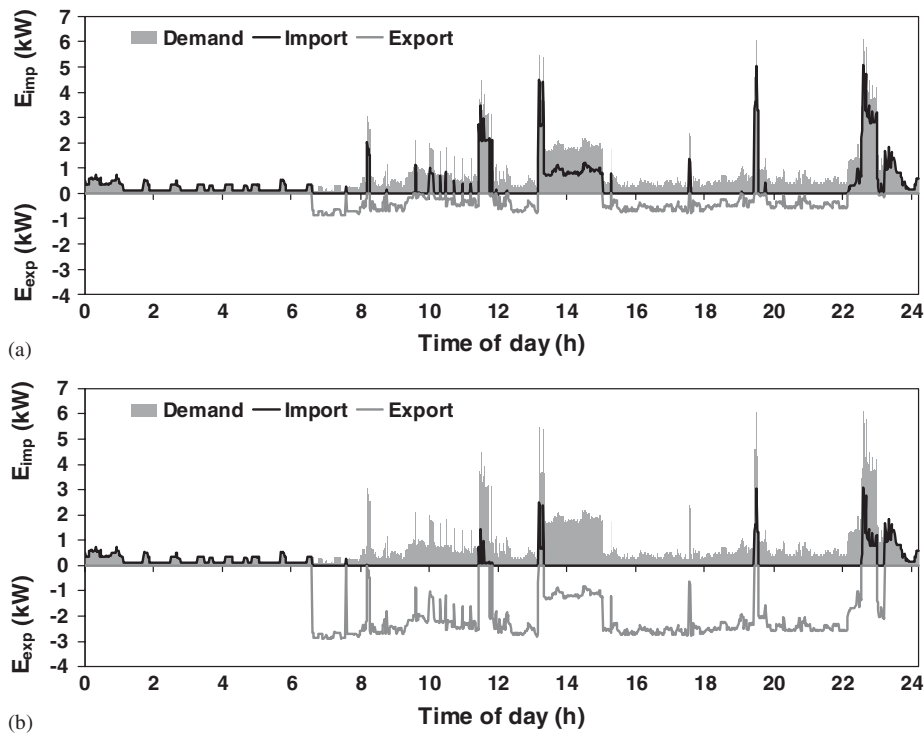


Fig. 2. Supply–demand matching of μ CHP systems for a single dwelling on January 25th. (a) 1 kW SE prime mover, (b) 3 kW FC prime mover.

Table 3

Key performance indicators of electrical performance of μ CHP Systems on January 25th for the single dwelling

Parameter	Original	1 kW SE and 1 kW FC	Fuel Cell 3 kW
e_{imp} (kWh)	17.8	7.6	3.4
Load factor (%)	12.2	6.2	4.6
Peak load (kW)	6.1	5.1	3.1
e_{exp} (kWh)	0	6.2	34.9
Capacity factor of E_{exp} (%)	0	24	49
Proportion of day with $E_{imp} = 0$ (%)	0	52	64
Run time (min)	0	988(69%)	

0.32 kW. This was largely due to the development of periods where there was no requirement to import network electricity (amounting to 52% of the day). Consequently, the daily load factor for network electricity decreased from 12.2 to 6.2%. An export flow of electricity from the dwelling to the network was produced with a total output, e_{exp} , of 6.2 kWh (cf. the demand, $e = 17.8$ kWh). The export profile from the dwelling is inherently intermittent in nature; its output may be described in terms of a capacity factor, relative to the installed capacity of an embedded micro-generator operating at full load continuously and its smoothness by a daily export factor (i.e. an average-to-peak ratio, analogous to the daily load factor of the demand profile). For the 1 kW systems the capacity factor of the exported electricity was 26%, while the daily export factor was 29.6%.

The increased electrical output of the simulated 3 kW FC system magnifies the impact of μ CHP operation with e_{imp} falling to just 19% of the demand (Fig. 2b, Table 3). The load factor was reduced further to 4.6% as the total period of the day for which $E_{imp} = 0$ rose to 62%. Network electricity is now only required during

periods of high demand and during periods when no thermal demand is present (i.e. night time). The cumulative export flow, e_{exp} , was 34.9 kWh, which is almost twice the value of e . This high value of e_{exp} relative to the 1 kW systems yields a high capacity factor of 49% and a daily export factor of 50.6%. However, the capacity factor and export factor decrease on days of intermediate and low thermal demand, because the export is more intermittent (e.g. for April 29th the 3 kW system yields capacity and export factors of 34% and 36%, respectively.)

For days of the year of lower thermal demand, the electrical efficiency of the prime mover has a considerable impact on the run time of the μ CHP system. Figs. 3–5 indicate the cumulative electrical energy imported from the network to the dwelling for January 25th, April 29th and August 21st, respectively. When

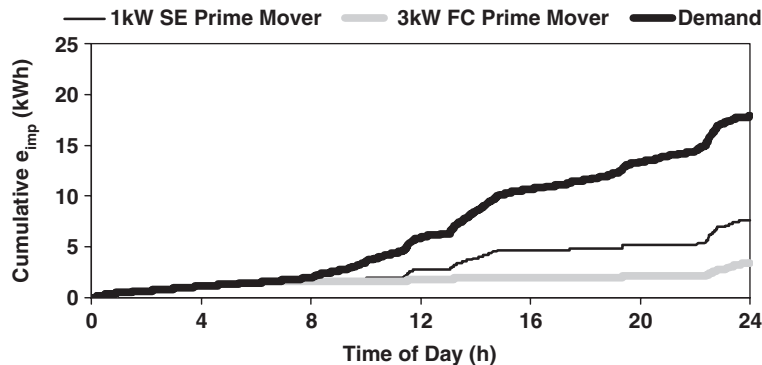


Fig. 3. Impact of μ CHP on cumulative electrical energy delivered to a single dwelling on January 25th.

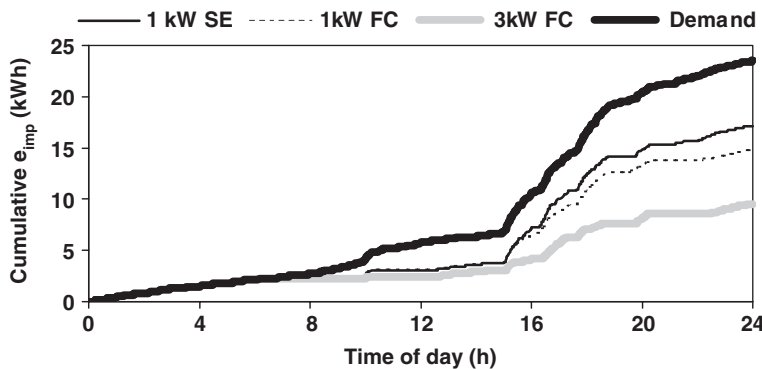


Fig. 4. Impact of μ CHP on cumulative electrical energy delivered to a single dwelling on April 29th.

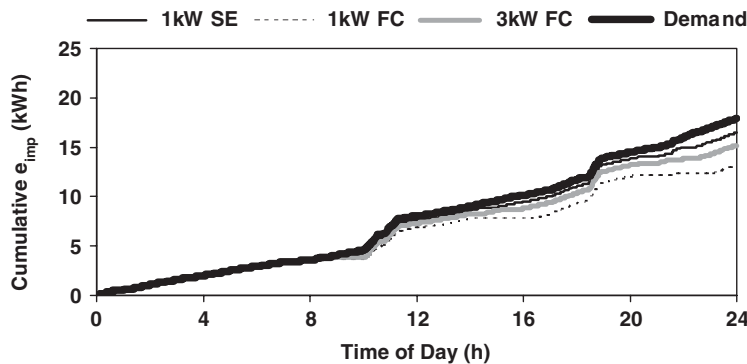


Fig. 5. Impact of μ CHP on cumulative electrical energy delivered to a single dwelling on August 21st.

Table 4

Key performance indicators of annual electrical performance of μ CHP systems for the single dwelling

μ CHP system	Season	e_{imp} (% of P_e)	e_{imp} (kWh)	e_{exp} (kWh)	Run time (%)
1 kW Stirling engine	Full year	75	4334	986	30
	Heating (Nov–Mar)	61	1557	611	50
	Mid (Apr, May, Oct)	81	1112	224	23
	Summer (Jun–Sept)	90	1665	151	12
1 kW Fuel cell	Full year	64	3739	1502	43
	Heating	57	1467	698	54
	Mid	67	929	412	40
	Summer	72	1343	392	33
3 kW Fuel cell	Full year	54	3118	6346	37
	Heating	35	892	3636	53
	Mid	60	834	1500	32
	Summer	75	1392	1210	20

the cumulative energy is increasing a load is being placed on the network, but when the gradient is zero all of the demand is being met by the μ CHP system. On January 25th, the impact of μ CHP discussed above is reflected by substantial periods of zero gradient (Fig. 3), while on April 29th, the 1 kW SE, 1 kW FC and 3 kW FC reduce e_{imp} by 27%, 37% and 60%, respectively (Fig. 4). Under the considered control regime, during the period 19:45–20:15 on April 29th none of the μ CHP systems could operate (due to the heat limit effect). The μ CHP systems would therefore be unable to contribute to this significant period of network demand if operated under the considered control regime. On August 21st the low thermal demand results in only short operational periods and the electrical efficiency has a considerable influence on run time (Fig. 5). The 1 kW FC system, with the lowest thermal output, yields the largest reduction in e_{imp} on this day, because it is able to operate when the other two systems remain shut down (e.g. between 14:00 and 16:12). However, it should be noted that the peak load of the dwelling on this day (6.5 kW) was not reduced by any of the μ CHP systems.

The seasonal nature of μ CHP electricity generation may be illustrated further by considering annual performances computed from 1-min data (Table 4). During the heating season each of the μ CHP systems is operational for greater than 50% of the available time and requirements for network electricity are minimised while e_{exp} is maximised. The impact of thermal output in curtailing the operational time of the system is more keenly felt in the summer months (June–September) where, for instance, the daily run time of the SE μ CHP system falls to 12% (179 min) and the proportion of the electrical demand met falls to 10%. The 1 kW FC meets a greater proportion of the dwelling's electrical demand during the summer than the 3 kW FC because of its lower thermal output.

3.2. Supply/demand matching at the distribution transformer

The impact of μ CHP penetration level, n , within the housing stock on aggregate load profiles when identical μ CHP systems are applied to individual homes within a group of 13 dwellings was investigated. The exported electricity from μ CHP systems that cannot be used within the group is assumed to represent the reverse power flow at the LV transformer. An after diversity maximum demand (ADMD) value of 2.0 kW has been reported for a dwelling in a typical housing estate [22]. The ADMD values for the considered group on January 25th, April 29th and August 21st were 2.08, 2.19 and 1.83 kW, respectively (Table 5). For each of these days the impact of diversity of demand on the ADMD diminishes substantially once the aggregate demand profile comprises at least 5 dwellings. The analysis presented here of the effect of applying μ CHP systems to various homes within a 13 home dataset is therefore considered to provide a good indication of the impact of μ CHP deployment on a transformer in the LV network that is dedicated to supplying domestic users.

As applies for the single dwelling analysis, the overall performances of the 1 kW SE and 1 kW FC systems on January 25th are almost identical. The effect of increasing penetration levels of the 1 kW systems within the

Table 5
Seasonal performance of μ CHP systems at different penetration levels for the group of dwellings

Date	Property	No CHP	1 kW SE		1 kW FC		3 kW FC	
			$n = 23\%$	$n = 77\%$	$n = 23\%$	$n = 77\%$	$n = 23\%$	$n = 77\%$
January 25th	ADMD (kW)	2.08	1.85	1.31	1.85	1.31	1.39	0
	e_{imp} (kWh)	266.3	210.3	87.9	208.7	85.8	100.6	0
	e_{exp} (kWh)	0	0	8.4	0	9.1	6.8	302.4
	Load factor (%)	40.9	36.6	21.3	36.9	20.8	23.1	0
April 29th	ADMD (kW)	2.19	1.96	1.73	1.96	1.5	1.5	0.37
	e_{imp} (kWh)	235.2	201.6	119.7	198.2	86.7	130.3	8.3
	e_{exp} (kWh)	0	0	1.8	0	3.8	1.5	205
	Load factor (%)	34.3	32.8	22.0	32.3	18.4	27.7	7.0
August 21st	ADMD (kW)	1.83	1.83	1.78	1.83	1.63	1.83	1.78
	e_{imp} (kWh)	255.4	251.4	224.9	245.3	178.1	234.3	132.1
	e_{exp} (kWh)	0	0	0	0	0	0	13.9
	Load factor (%)	44.6	43.9	40.3	42.9	34.9	40.9	23.6

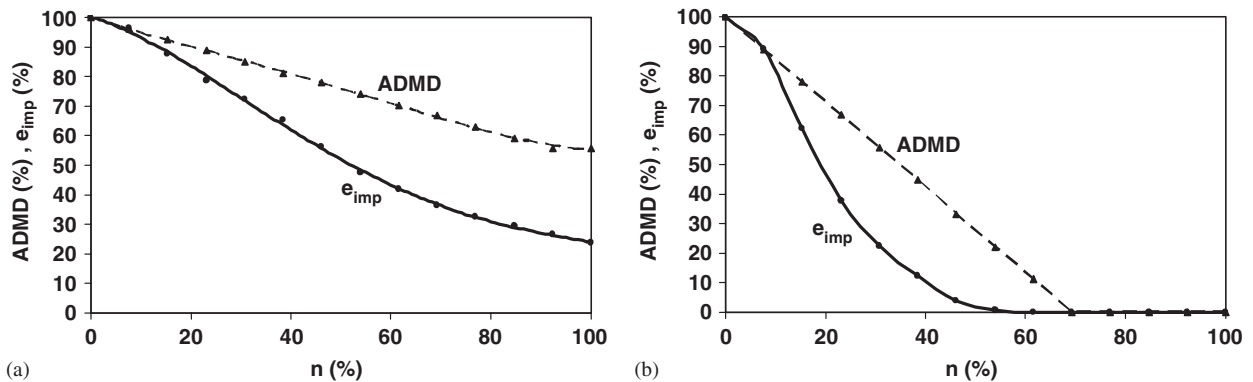


Fig. 6. Effect of penetration of μ CHP systems on ADMD and e_{imp} for a group of 13 dwellings on January 25th. (a) 1 kW SE, (b) 3 kW FC.

group is to reduce both ADMD and e_{imp} . However, the proportional decrease in e_{imp} is much more marked than that for ADMD. For example, when $n = 38\%$ (5 dwellings), ADMD = 1.69 kW (a 19% reduction) while $e_{imp} = 173$ kWh (a 35% reduction) (Fig. 6a). With the 3 kW systems, the requirement for e_{imp} disappears when $n > 69\%$ (9 dwellings) (Fig. 6b). Below this penetration level, the disparity in impact on e_{imp} and ADMD of the 3 kW μ CHP systems is more marked than for the 1 kW systems. For instance, when $n = 38\%$, the 3 kW systems reduce ADMD to 0.93 kW (a 56% reduction) and e_{imp} to 32.5 kWh (an 88% reduction).

Reduced ADMD values for network electricity due to the penetration of μ CHP systems would effectively permit more houses to be connected to an existing LV transformer or reduce infrastructure costs for say a new build housing estate that includes a proportion of homes fitted with μ CHP systems. For example, a 400 kVA–1 MVA transformer could be used to service 192 homes at an ADMD of 2.08, but if a μ CHP penetration level of 23% was applied, the same transformer could service 216 homes (for a deployment of 1 kW μ CHP systems) or 288 homes (for a deployment of 3 kW μ CHP systems). However, the precise impact of reduced ADMD values on LV planning will be significantly affected by the reliability of μ CHP systems, which is currently unknown.

The aggregate maximum demand for the group on January 25th was 27.0 kW at 22:07, the daily load factor was 41.0% and the daily electricity requirement was 266.3 kWh. A modest deployment ($n = 23\%$) of 1 kW SE μ CHP systems caused the peak load to decrease by 3 kW (11%), e_{imp} to decrease by 21% and the load factor to

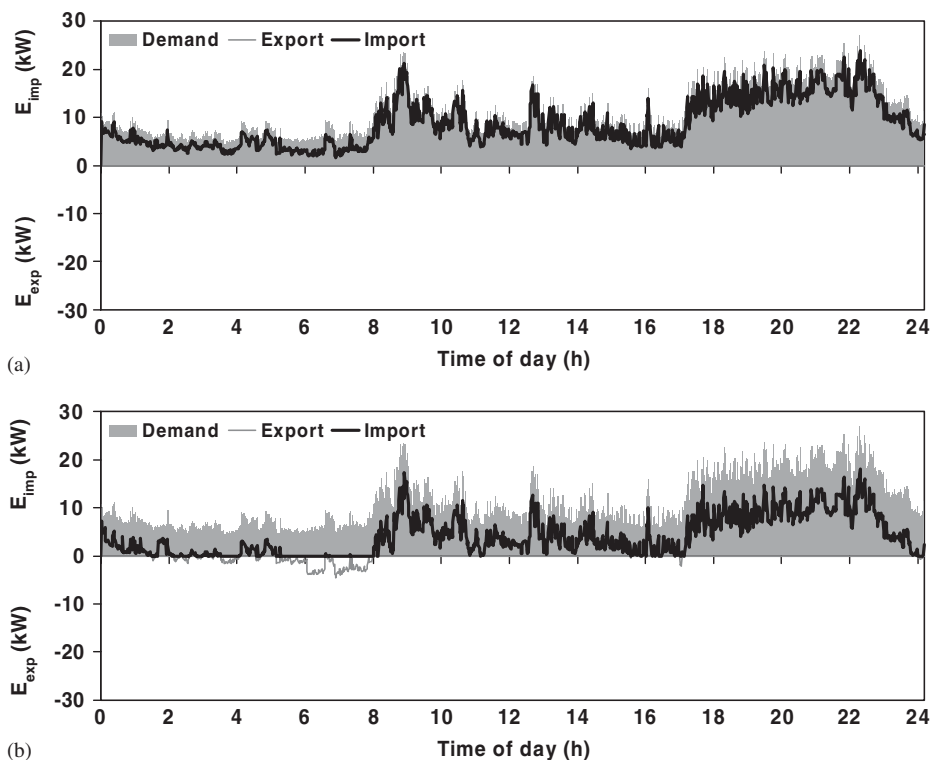


Fig. 7. Supply demand matching of μ CHP systems with $n = 23\%$ in a group of 13 dwellings on January 25th. (a) 1 kW SE prime mover, (b) 3 kW FC prime mover.

fall to 36.3% (Fig. 7a). At least one μ CHP system was active at any minute of this day, with the μ CHP utilisation factor varying from 57% during the night (00:00–06:00 h) to 100% during periods when demand was increasing rapidly. No reverse flow of electricity was exported from the group to the MV network.

A similar deployment ($n = 23\%$) of 3 kW FC systems caused the peak load to decrease by 9 kW (33%) and a reduction in e_{imp} of 62% (Fig. 7b). Periods existed when there was no requirement to import network electricity to meet demands occurring within the group—the total time when $E_{imp} = 0$ amounting to 285 min (20% of the day). Consequently, two fairly distinct periods of demand for network electricity occurred, nighttime and daytime/evening, with commensurate gradient changes specific to this deployment scenario. The daily load factor fell to 23.1%.

As the penetration of μ CHP systems increases, the requirement for network electricity falls and the length of time when no imported electricity is required increases. For a very high deployment ($n = 77\%$) of 1 kW SE μ CHP systems, e_{imp} falls by 67%, the peak load falls by 10 kW (37%) and $E_{imp} = 0$ for 329 min (23% of the day), with three distinct periods of demand for network electricity now occurring (Fig. 8a). The corresponding load factor is reduced to 21.3%. At $n = 77\%$, a deployment of 3 kW FC systems would satisfy the total requirement and produce an export of electrical energy, e_{exp} , of 302.4 kWh compared to the original demand, e of 266.3 kWh (Fig. 8b).

The aforementioned seasonal effects of μ CHP operation for the single dwelling are also prevalent at group level (Table 5). The seasonal variation is most pronounced for the 1 kW SE μ CHP systems as a result of their high thermal output. For instance, for a deployment with $n = 77\%$, the daily e_{imp} requirement for the group is reduced by 67%, 49% and 12% on January 25th, April 29th and August 21st, respectively. The ADMD on August 21st is reduced to 1.78 kW, but on January 25th it is reduced to 1.31 kW. Seasonal variation is also present, but less marked, for the FC systems—at $n = 77\%$, the 3 kW μ CHP systems remove entirely the requirement for network electricity on January 25th, while on August 21st they reduce it by only 48%.

So although μ CHP systems may reduce peak loads placed on transformers, these seasonal effects suggest that LV network planners will need to place greater emphasis on summer time demand, especially if high

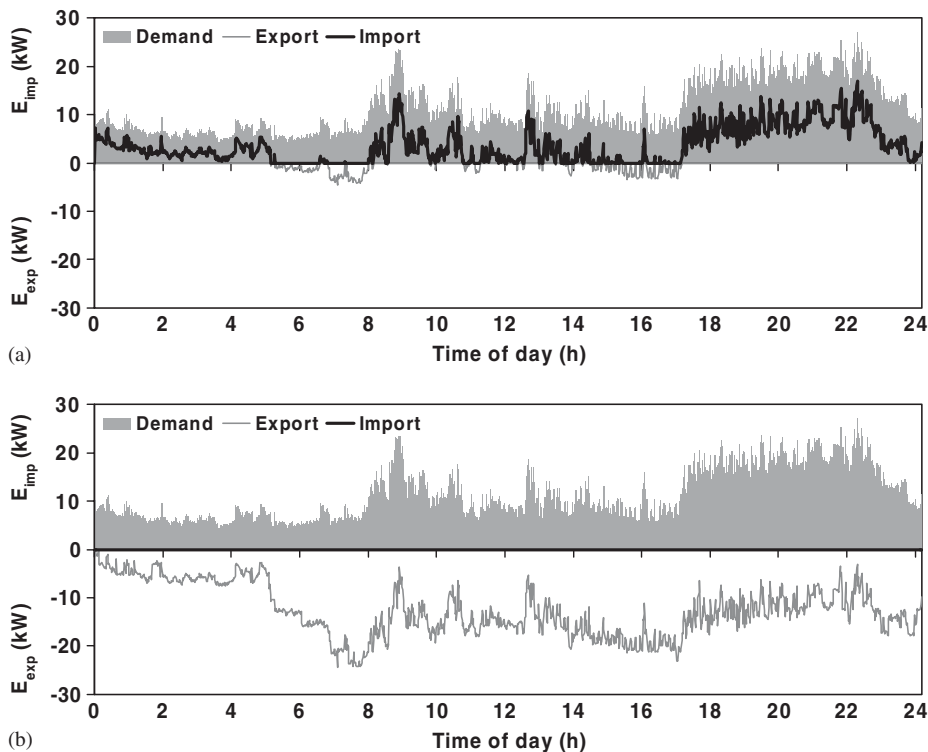


Fig. 8. Supply demand matching of μ CHP systems with $n = 77\%$ in a group of 13 dwellings on January 25th. (a) 1 kW SE prime mover, (b) 3 kW FC prime mover.

penetration levels are achieved, or individual μ CHP systems of high capacity are installed at more modest penetration levels. Furthermore, if the possible growth in domestic air conditioning is realised [14], μ CHP systems operating on a heat-led control logic may well be of limited value in diminishing peak load on a summer day. This reinforces the need to develop high efficiency prime movers and suggests a requirement for summer time control regimes (e.g. that enable water-heating demands to be met by recovered heat, while ensuring μ CHP system operation and air conditioning demand are in phase whenever feasible).

A deployment of μ CHP systems, regulated by the control logic considered here, will always serve to reduce the daily load factor of the profile placed on the network (Table 5). It is interesting to consider the impact of this in greater detail. Between 08:31 and 08:50 on January 25th, the positive gradient in aggregate demand from the group was 0.74 kW/min, while between 16:54 and 17:24, it was 0.43 kW/min. The 1 kW SE systems do not reduce the morning gradient until $n > 62\%$ or the evening gradient until $n > 46\%$. At these penetration levels, e_{imp} has been substantially reduced. However, a deployment of 3 kW systems has a greater impact on gradient change, with reductions occurring once $n > 23\%$, but at the expense of a rapidly diminishing daily requirement for network electricity.

This use of μ CHP to influence demand patterns and gradients provides additional complexity to the process of determining desired operational procedures. DSM techniques have previously been researched in order to modify the load profile of an individual dwelling [4]. The aggregate effect of doing so will be to increase the daily load factor placed on a distribution transformer, but the impact of applying such micro-DSM techniques is constrained, both by behavioural factors in households and the need for appliance manufacturers to re-engineer the load signatures of individual appliances. By focussing attention on the specification and control of μ CHP systems, a number of these constraints could be overcome effectively placing μ CHP as a buffer between domestic demand profiles and network load profiles. The development of prime movers of high electrical efficiency that can be readily controlled will serve to increase the scope for μ CHP systems to provide services in addition to those of meeting the dwelling's thermal demand and some part of its electrical demand.

Table 6

Key performance indicators for electricity exported from the group of dwellings on January 25th for the stated penetration levels

Property	1 kW SE		1 kW FC		3 kW FC	
	$n = 23\%$	$n = 77\%$	$n = 23\%$	$n = 77\%$	$n = 23\%$	$n = 77\%$
e_{exp} (kWh)	0	8.4	0	9.1	6.8	302.4
Export factor (%)	0	8.2	0	8.9	7.1	52.3
ADME (kW)	0	0.37	0	0.37	0.36	1.9
Capacity factor (%)	0	3.0	0	3.3	0.8	33.3

The amount of electricity exported from the group of dwellings outside of the heating season is not substantial. During the heating season, it only becomes substantial when both n and P_{oe} are relatively high. On January 25th, with $n = 77\%$, 1 kW SE systems provide an export of only 8.4 kWh (equivalent to approximately 3% of the daily requirement, e from the group) (Fig. 8a, Table 6). This contrasts with an e_{exp} of 302.4 kWh if 3 kW FC systems are deployed (with $n = 77\%$). This export flow is intermittent and variable (Fig. 8b), because it is a function of both the thermal demand (in determining the operational run time) and the electrical demand of each dwelling in the group. The associated export factor was 52.3%. Similarly a reverse flow after diversity maximum export (ADME) can be derived for a transformer serving a group of dwellings containing μ CHP systems. For example, a deployment of 3 kW FC systems with $n = 77\%$ resulted in an ADME of 1.9 kW, compared with an original (no CHP) ADMD value of 2.08 kW. The capacity factor of this export was 33% which, when compared with the aforementioned value of 49% for the single dwelling, indicates the extent to which electricity exported from individual dwellings can be utilised below the distribution transformer.

A deployment of high-efficiency prime movers of high output would result in export flows during the heating season that would make the domestic sector a significant net exporter of electricity to nearby consumers in the industrial and commercial sectors. However, reverse flows may cause problems for voltage control, protection and metering systems. At the level of the single dwelling, E_{exp} occurs on every day of the year for all of the μ CHP systems studied. However, much of this export can be utilised within the group and does not therefore reach the MV network. Export of electricity to the MV network is most prevalent on days when there is a high thermal demand. On January 25th, for the 1 kW μ CHP systems, an E_{exp} flow through the transformer occurred when $n > 46\%$. This export occurred intermittently between 05:30 and 07:45 h. For the 3 kW FC systems, similar exports occurred when $n > 15\%$ between the hours 02:30 and 07:50. On August 21st, E_{exp} did not occur for the 1 kW systems at any penetration level, but a deployment of the 3 kW systems with $n > 38\%$ resulted in export flows between the hours of 06:00 and 08:30. The timing of E_{exp} is an important determinant of its usefulness to the network. At times of peak load from the group of dwellings on January 25th (ADMD = 2.08 kW), no electricity was exported to the MV network and e_{imp} was reduced by 41%. At the time of minimum load (average load per dwelling = 0.33 kW), e_{imp} was reduced to zero and an export flow constituting 29% of the minimum demand was produced. It should be noted that this dislocation between apparent times of peak electrical load and the operating times of μ CHP systems, when controlled to follow thermal demand, heightens the need to develop μ CHP system designs that promote increased operational functionality throughout the year.

4. Discussion

The μ CHP approach has the capacity to reduce significantly the annual demand placed on the electricity network by the UK domestic sector. At the level of the single dwelling, demand was reduced by 25% for the simulated 1 kW SE system and by 46% for the 3 kW FC system. In general, the demand for network electricity from a single dwelling employing a μ CHP system will be characterised by greater intermittency and a much-reduced daily load factor.

The operational performances of μ CHP systems are highly seasonal, linked as they are to the thermal demands occurring within dwellings (i.e. for space heating and/or hot water). This seasonal influence decreases

as the electrical efficiency of the μ CHP prime mover increases. The 1 kW SE system (with an electrical efficiency of 15%) reduces the amount of energy imported by the dwelling from the network by 39% during the heating season, but only 10% during the summer months. By comparison, a 1 kW FC prime mover of 50% electrical efficiency achieves reductions of 43% and 28% during the heating season and summer months, respectively.

The impact of deploying identical μ CHP systems within a group of dwellings on the aggregate daily load profile is a function of the μ CHP penetration level within the group, the thermal demand profile in each dwelling and the capacity and efficiency of the prime mover. For the heat-led control strategy considered here, the effect of the μ CHP systems was always to reduce the daily load factor for network electricity. The load factor decreases with increasing prime mover capacity, efficiency and daily run time. In general (for the considered ranges of $1\text{ kW} < P_{oe} < 3\text{ kW}$ and $15\% < \zeta_e < 50\%$), the daily requirement for network electricity for a low penetration deployment of high-capacity high-efficiency systems is similar to that for a high penetration deployment of low-capacity low-efficiency systems. For example, at a penetration level of 23%, a 3 kW FC system of 50% electrical efficiency was predicted to reduce the import requirement by 8%, 45% and 62%, respectively on a summer day, a day in mid season and a day in the heating season, while corresponding reductions of 12%, 49% and 67% were predicted for a 1 kW SE system at a penetration level of 77%.

On January 25th, operation of the μ CHP systems was not a function of their thermal output because of the high thermal demand in each dwelling. The average run time across the 13 dwellings was 1092 min (76% of the day) causing a substantial reduction in the requirement for network electricity. The coincidence of μ CHP operation and peak demand from the group of dwellings is high, particularly during the heating season when μ CHP systems tend to produce electricity that has base load characteristics because of the long run times. The ADMD for a group of dwellings will therefore be reduced by deploying μ CHP systems, but it should be noted that the relative reduction in ADMD is always less than the reduction in e_{imp} .

The deployment of 1 kW μ CHP systems does not lead to any significant reverse flows through the distribution transformer until the penetration level exceeds about 50%. Conversely, the deployment of 3 kW systems of high electrical efficiency is predicted to remove the load from the group of dwellings on days of high thermal demand and result in significant export flows, for penetration levels of greater than about 40%. If very high penetration levels of 3 kW FC systems were achieved locally, the upstream energy flows at transformers would exceed the conventional (no CHP) downstream flows.

The impact of μ CHP systems on e_{imp} , ADMD, the load factor and e_{exp} was extremely seasonal. During the summer months, the 1 kW SE μ CHP systems had an average run time across the group of 187 min (13% of the day), which was approximately one-sixth of the average heating season run time. Consequently, as the penetration level of μ CHP systems increases, the electrical load placed on the network during the summer months will assume greater importance. A balance point may ultimately be reached whereby the climatic variation and the behaviour of the domestic sector during the summer months will become the determining factor in LV network planning. This balance point will be reached more quickly if μ CHP systems of high output and high electrical efficiency are deployed.

For the heat-led control strategy adopted here, the simulated μ CHP systems have the potential to reduce CO₂ emissions attributable to the investigated dwelling by 10%, 16% and 40% for the 1 kW SE, 1 kW FC and 3 kW FC systems, respectively [2]. Emissions reductions of this scale for a single change per dwelling are substantial, when considered in the context of achieving a 60% reduction in national CO₂ emissions by 2050 [14,23]. Furthermore, μ CHP deployment reduces network utilisation at times of peak demand during the heating season and reduces the ADMD placed on distribution transformers, but at the expense of the load factor for centrally generated electricity. For the electricity supply industry, these characteristics imply a substantial decrease in revenue from sales to the domestic sector and an extra difficulty in matching large central plant to a more variable load profile. It is therefore important that the CO₂ reduction estimates associated with a mass uptake of μ CHP systems in the domestic sector, are appropriately inter-related with those associated with the time-varying operation of the primary thermal generation plant that serve all sectors. The results presented here are based on the analysis of one control regime and the mass deployment of a single type of μ CHP system within a group of dwellings. Defining an optimal control situation is a non-trivial task, demanding consideration of a large number of engineering and economic variables. Engineering research and

policy initiatives should therefore aim to ensure that a CO₂-optimal solution emerges, if the future power system is to include a large deployment of μ CHP systems.

If μ CHP deployment is not integrated within energy policy, it is likely that the overall carbon saving will be compromised. The findings of this investigation suggest that the μ CHP approach requires further research to identify (i) optimal configurations, control regimes and penetration levels; (ii) the extent to which increased variability in the network load profile, as a result of μ CHP, will affect the supply/demand matching of primary thermal generation plant; and (iii) the capacity of networks to absorb increased levels of dispersed renewable generation at MV and LV level due to the application of μ CHP systems.

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